

# 21-cm radiation: A new probe of fundamental physics

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## Abstract

New low frequency radio telescopes currently being built open up the possibility of observing the 21-cm radiation before the Epoch of Reionization in the future, in particular at redshifts  $200 > z > 30$ , also known as the dark ages. At these high redshifts, Cosmic Microwave Background (CMB) radiation is absorbed by neutral hydrogen at its 21-cm hyperfine transition. This redshifted 21-cm signal thus carries information about the state of the early Universe and can be used to test fundamental physics. We study the constraints these observations can put on the variation of fundamental constants. We show that the 21-cm radiation is very sensitive to the variations in the fine structure constant and can in principle place constraints comparable to or better than the other astrophysical experiments ( $\Delta\alpha/\alpha = < 10^{-5}$ ). Making such observations will require radio telescopes of collecting area  $10 - 10^6 \text{ km}^2$  compared to  $\sim 1 \text{ km}^2$  of current telescopes. These observations will thus provide independent constraints on  $\alpha$  at high redshifts, observations of quasars being the only alternative. More importantly the 21-cm absorption of CMB is the only way to probe the redshift range between recombination and reionization.

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## I. THE LAST FRONTIER IN COSMOLOGY

In the standard model of cosmology the electrons recombine with protons and heavy nuclei, mostly helium, to form neutral atoms at a redshift of around  $z \sim 1100$ . The mostly neutral baryonic gas then undergoes gravitational collapse to form the first stars which then reionize the Universe. The process of reionization is expected to start at around  $z \lesssim 30$  and end by  $z \sim 6$ . The era between recombination and reionization has come to be known as the dark ages due to the absence of any stars or other light emitting collapsed objects. There is however the CMB which gets absorbed by the hydrogen gas at 21-cm rest wavelength corresponding to the hyperfine transition of ground state of hydrogen. The observation of these dark ages using the 21-cm line is considered to be the last frontier in cosmology due to the new information it will bring about this hitherto unexplored redshift range and also because the amount of information we can get from the 21-cm observations of dark ages is many orders of magnitude more than is possible by any other cosmological probe.

We can probe the big bang nucleosynthesis at a redshift of  $z \sim 10^9$  by measuring the abundance of light elements, this gives information only about the average properties of the Universe. CMB is a snapshot of Universe at  $z \sim 1100$  and has information on scales  $\gtrsim 10$  Mpc. Below 10 Mpc Silk damping causes the CMB power spectrum to drop rapidly making it hard to measure. Observations of galaxies, clusters of galaxies and Ly $\alpha$  forest probes  $z \gtrsim 6$  also on scales  $> 10$  Mpc. On small scales the matter perturbations at low redshifts become non-linear making it hard to reconstruct the initial conditions or constrain fundamental physics. The 21-cm observations will allow us to probe a new redshift range of  $30 \gtrsim z \gtrsim 200$ , which is not accessible by any other method, on scales down to  $\sim$  few kpc and use that information to constrain initial conditions and fundamental physics.

## II. 21-CM COSMOLOGY

We refer to the review paper by Furlanetto et al. [1] for the details of 21-cm cosmology. After recombination although most of the plasma has recombined, some residual ionization remains with ionization fraction  $\sim 10^{-4}$ . These remaining free electrons scatter off CMB photons transferring energy from the CMB to gas. The baryon temperature is thus maintained at that of CMB up to a redshift of  $\sim 500$  when Thomson scattering becomes

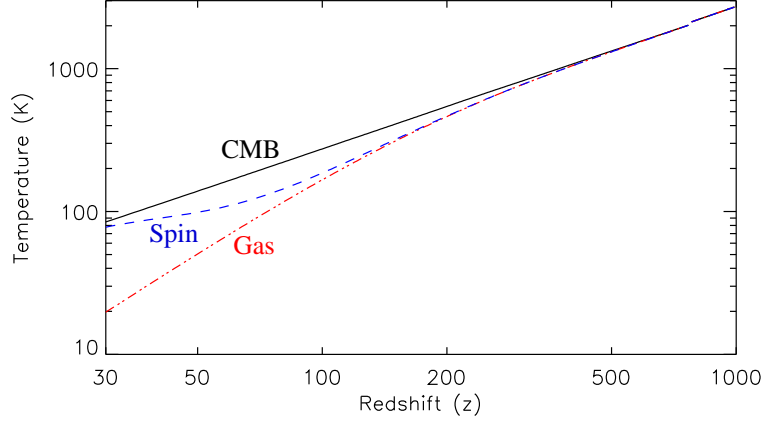


FIG. 1: Thermal history of the Universe. Collisions keep the spin temperature close to gas temperature at high redshifts while at low redshifts coupling to CMB pushes the spin temperature towards CMB temperature.

inefficient in heating the gas and thereafter baryons cool adiabatically due to the expansion of the Universe. This is shown in Figure 1. Also shown in the figure is the spin temperature defined by relating the population levels in the two hyperfine states of hydrogen by the Boltzmann factor,  $\frac{n_t}{n_s} = \frac{g_t}{g_s} e^{-T_*/T_{spin}}$ , where  $n_t$  and  $n_s$  are number density of hydrogen atoms in excited triplet and ground singlet state respectively,  $g_t$  and  $g_s$  are the corresponding statistical weights,  $T_* = 0.068K$  is the energy difference between the two levels and  $T_{spin}$  is the spin temperature. Its behavior can be understood as follows. At high redshifts the density of gas is high and the spin changing collisions between the hydrogen atoms is the dominant effect determining the population levels in two states establishing local thermodynamic equilibrium. Thus at high redshifts spin temperature is equal to the kinetic temperature of gas. At low redshifts as the density of gas drops collisions becomes inefficient compared to the absorption and emission of CMB photons in determining the population levels. The spin temperature thus approaches that of CMB. The mean observed brightness temperature defined by the Rayleigh-Jean formula  $T_b = I_\nu c^2 / 2k_B \nu^2$ , where  $I_\nu$  is the intensity difference due to absorption/emission of 21-cm photons, is given by

$$T_b = \frac{(T_s - T_{CMB})\tau}{(1+z)}, \tau = \frac{3c^3 \hbar A_{10} n_H}{16k_B \nu_{21}^2 (H + \frac{dv}{dr}) T_s}$$

where  $\tau$  is the optical depth,  $H$  is Hubble parameter,  $k_B$  is Boltzmann constant,  $n_H$  is number density of neutral hydrogen,  $\nu_{21} = k_B T_*/h \sim 1420\text{MHz}$ ,  $v$  is the peculiar velocity of gas and  $r$  is the comoving distance. As shown in Figure 1, between recombination and

reionization the spin temperature is less than the CMB temperature which gives a negative  $T_b$  corresponding to absorption. The redshift of  $200 \gtrsim z \gtrsim 30$  corresponds to the observed frequency range of  $7\text{MHz} \lesssim \nu_{\text{obs}} \lesssim 46\text{MHz}$ . At around redshift of  $z \sim 30$  first stars are expected to form which would heat and ionize the gas complicating the prediction of the 21-cm signal due to unknown astrophysics.

Perturbations in the baryon density and temperature gives rise to perturbations in the 21-cm absorption signal and we can compute the angular power spectrum of the perturbations as in case of CMB [2, 3]. Figure 2 shows the 21-cm angular power spectrum for different redshifts. Also shown for comparison is the CMB angular power spectrum. The CMB power spectrum is suppressed due to free streaming of photons for angular wavenumber  $\ell \gtrsim 3000$ . Since the 21-cm power spectrum traces the matter density perturbations we can probe much smaller scales,  $\ell \sim 10^6$ . For  $\ell > 10^6$  21-cm power spectrum is also suppressed due to baryon pressure. Also we can measure 21-cm power spectrum at many redshifts, the number being determined by the bandwidth of the telescope. Thus 21-cm power spectrum probes a volume of the early Universe in contrast with CMB which probes a surface (of some finite thickness). The amount of information can be summarized by number of modes we can measure, which for 21-cm is  $\sim \ell_{\text{max}}^3 \sim 10^{16}$  compared with CMB which is  $\sim \ell_{\text{max}}^2 \sim 10^7$ . Thus there is many orders of more information available, in principle, from 21-cm observations of dark ages. More importantly the perturbations are linear down to very small scales and can be accurately calculated and used to reconstruct initial conditions or constrain fundamental physics.

### III. FUNDAMENTAL PHYSICS WITH 21-CM RADIATION FROM DARK AGES

The enormous amount of information accessible with 21-cm observations of dark ages provides an opportunity to constrain fundamental physics with high precision, for example initial conditions of the Universe [5], grand unified theories and superstring theory physics [6] and variation of fundamental constants [7]. One of the important questions in fundamental physics is whether the fundamental constants vary in space and time. Since 21-cm signal depends on atomic physics it can be used to constrain the related fundamental constants like the fine structure constant ( $\alpha$ ) and electron to proton mass ratio  $\mu = m_e/m_p$ . In fact 21-cm physics is highly sensitive to the variation in  $\alpha$ . The rest frequency  $\nu_{21} \propto \alpha^4$ , Einstein

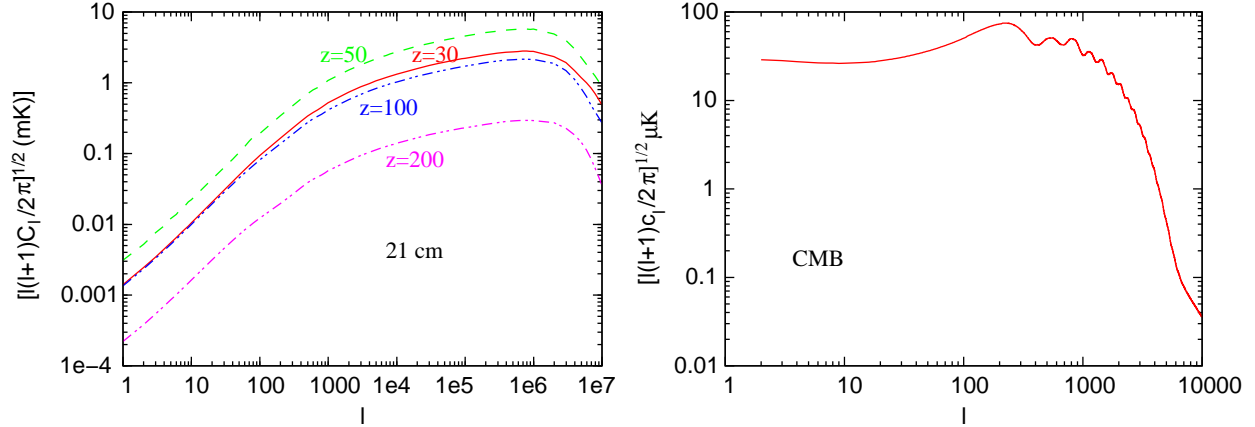


FIG. 2: 21cm angular power spectrum and CMB power spectrum. Numerical calculations were done using CMBFAST [4]

coefficient  $A_{10} \propto \alpha^{13}$ , Thomson cross section  $\sigma_T \propto \alpha^2$  and the ionization fraction  $x_e$  is determined by recombination physics which is also sensitive to  $\alpha$  [8, 9]. The  $\alpha$  dependence of spin change cross sections due to collisions between hydrogen atoms needs to be calculated ab-initio [7] and is found to be  $\kappa_{10} \propto \alpha^{2-8}$  where the index on  $\alpha$  depends on gas temperature. Taking this  $\alpha$  dependence into account we can do a Fisher matrix analysis [10] of constraints we can get on the variation of  $\alpha$ . The result of such an analysis is shown in Figure 3. Different curves are for the radio telescopes of different sizes labeled by the collecting area (with the aperture filling factor assumed to be unity). Although current telescopes like LOFAR do not have enough collecting area to provide interesting constraints, a telescope few times bigger can surpass the CMB and big bang nucleosynthesis constraints while a telescope with a thousand square kilometer of collecting area will be able to surpass the current best quasar constraints.

#### IV. CONCLUSIONS

We have shown that the 21-cm observations of the dark ages can provide very tight constraints on the variation of the fine structure constant. In addition we should also expect similar sensitivity to the electron to proton mass ratio. This is easily seen by observing that  $A_{10} \propto \frac{1}{m_e^2} \left( \frac{m_e m_p}{m_e + m_p} \right)^3$ ,  $\sigma_T \propto \frac{1}{m_e^2}$  etc. The spin change collision cross section also depend on  $m_e/m_p$  through the kinetic term in the electronic Hamiltonian of the hydrogen molecule. One of the challenges in observing this 21-cm cosmological signal is the presence of the

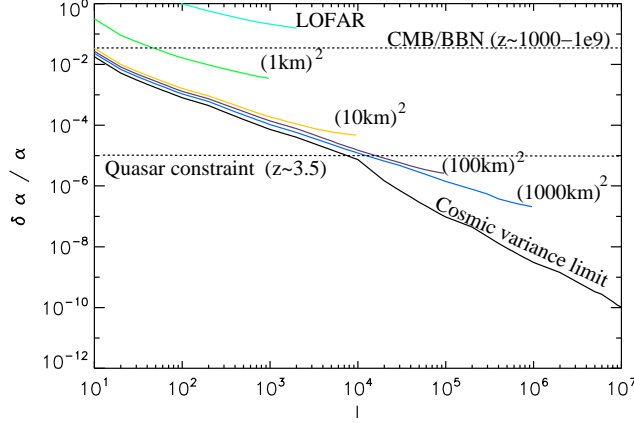


FIG. 3: Constraints on  $\alpha$  from 21-cm observations of dark ages for different radio telescopes labeled by collecting area. Also shown is a current telescope, LOFAR, that is currently operating in Europe.

synchrotron foregrounds. The sky noise due to the synchrotron foregrounds in the galaxy is expected to be  $T_{sky} \sim 19000K \left( \frac{22MHz}{\nu} \right)^{2.5}$  [11]. This is many orders of magnitude larger than the cosmological signal which is of the order of  $\sim mk$ . The foregrounds can still be removed from the cosmological signal due to the following reason [10]. The foregrounds are expected to be correlated in frequency while the cosmological signal traces a gaussian random field and would be uncorrelated for frequencies sufficiently separated. Thus the detection of the cosmological signal is challenging but possible. Interstellar scattering may limit the smallest scales that are observable to  $\ell \lesssim 10^6$  [12]. Terrestrial EM interference from radio/TV/communication and Earth's ionosphere poses problems for telescopes on ground. Earth related problems may be solved by going to the Moon and there are proposals for doing so, one of which is the Dark Ages Lunar Interferometer (DALI) [13]. In conclusion 21-cm cosmology promises a large wealth of data with which to constrain and learn about fundamental physics.

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